# SLIDING MODE-BASED TRACTION CONTROL FOR AN AUTONOMOUS MARTIAN ROVER

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## ABSTRACT

A traction control system was developed for an autonomous Martian rover using a sliding mode controller. The main inspiration for this project was NASA's Mars rover, Curiosity, which suffered severe wheel damage due to the lack of an effective traction control system. A control system was sought out to effectively prevent wheel damage, slippage, and soil failure for a Martian rover. It was initially hypothesized that a sliding mode controller would be most effective to control the vehicle's traction. A Simulink model was created with a deformable soil-rigid tire mathematical model in order to simulate the traction control system. The sliding mode controller was tested to be more robust and stable compared to a proportional-integral-derivative (PID) controller for the rover. The results elaborate the possible applications for this project, which spans across commercial and military rovers, rescue robots, and planetary rovers in the private and global space industry.

## 1 INTRODUCTION

Traction control has been a growing concern for the robotics and automotive industry. For example, traction control can be applied to hybrid cars, rescue robots, and planetary rovers [2,8,12]. The main inspiration for this research was the severe damage of the wheels of the Mars Rover, Curiosity, that resulted from an incomplete understanding of the Martian terrain and a lack of a suitable traction control system[1]. NASA later produced an algorithm to reduce further damage to the wheels and to continue its exploration of Mars, but this method was not in the scope of difficulty for this project[14]. Instead, a similar approach to Kazuya Yoshida's article about Slip-Based Traction Control was followed[17].

The goal of this research is to create a simulation to test a model-based traction control system for a Martian Rover, like Curiosity. This project consists of two main components: mathematical modeling of the vehicle-terrain interaction and the controller, which generates a voltage applied to the wheel's electric motor. This voltage forces the slip ratio to approach a desired value. In other words, the controller accelerates the vehicle efficiently in the deformable Martian terrain.

In Yoshida's research, a slip-based model was developed using the terramechanics, which is the study of soil properties, of a rigid wheel on loose-deformable soil[17]. The terrain model used in this article was the deformable soil-rigid tire model, which was then adopted into the current project[15]. This

FIGURE 1: *One of Curiosity's Damaged Wheels.*
DESCRIPTION: *The holes present on the middle tire, on the right side of the image, was caused by sharp rocks found in Gale crater. Due to the lack of a traction control system, the damage to the tire grew rapidly.*

model consists of several equations of terramechanics; specifically the interaction of wheeled vehicles on various surfaces. The equations involved model soil that is deformed by the vehicle's wheels, as well as the resistive and driving force and torque generated by the soil. These relations allow for a more accurate simulation for the soil and vehicle interaction. This model was also chosen based on the computing restrictions of the computer used. More advanced options like finite element models require computers with higher level of performance.

Another key component is the controller. In Yoshida's research, a proportional-integral-derivative controller (PID) was used to control the slippage[17]. After thorough investigation, a faster and more robust method was sought out. A faster method specifically meant a quicker settling time (time to reach 2% of the desired slip ratio value), and more robust method meant a controller that functions better with more uncertainties. The Sliding Mode controller was used for its robustness and effectiveness[5]. The more advanced controller is a nonlinear control method that uses a discontinuous control signal. It is a type of variable structure control, meaning it alters the dynamics of a nonlinear system by applying a switching control.

Mathworks' softwares Matlab and Simulink were integral tools used for this research[9]. Matlab is a programming tool with its own language that expresses matrix math more directly. Simulink is a program for modeling, simulating, and analyzing dynamical systems. Its main interface is a block diagramming tool that allows the user to model and simulate a system made up of various interconnected equations. They were ideal for this project because Simulink and Matlab are frequently used for professional vehicle based-control system design in the field. Simulink is user-friendly for mathematical modeling because of its block-based coding. This means that instead of writing lines of code, the control system can be designed with simple "blocks" that represent mathematical operations and tasks. Matlab was useful for inputting initial conditions and extracting results for plots. Both of these softwares were used together to simulate and extract results.

$$F_d = M\dot{v}_x$$

$$T_m - T_s = J_\omega \dot{\omega}_w$$

$$\lambda = \frac{r\omega_w - v_x}{r\omega_w}$$

EQUATION SET 1: *Vehicle Model and Slip Ratio.*

## 2 MODELING

A negative feedback system occurs when the output of a system is fed back into itself in order to influence its output. These system configurations are required for most control methods. In order to model a traction control system with block diagrams in Simulink, three basic components of a negative feedback loop are needed:

1. The plant is the mathematical model of the dynamic equations of the problem.
2. The actuator is the controlled motor.
3. The controller is inputted with the error of the feedback loop (the desired slip ratio minus the plant's modeled slip ratio) and outputs the voltage applied to the actuator.

To begin understanding the problem of slip-based traction control on deformable soil, a basic understanding of a vehicle control system was established through the exploration of a simple Anti-lock Braking System (ABS). Two examples were used as a starting point: the first being an example from Mathworks' website and the second being a rudimentary Simulink block diagram[4,10]. The second example incorporates the quarter car model for the vehicle's motion equations.

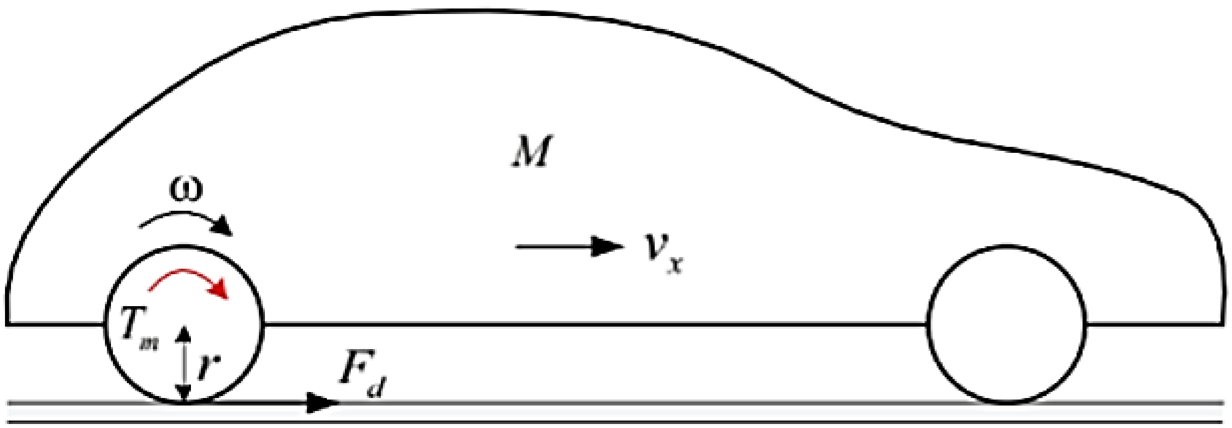



FIGURE 2: *Vehicle Model.*
DESCRIPTION: *This diagram represents a simplified model, which focuses on a single wheel's dynamics. $M$ is the mass of the car, $r$ is the radius of the wheel, $v_x$ is the vehicle's velocity, $\omega$ is the angular velocity of the wheel, $F_d$ is the driving force, and $T_m$ is the motor torque.*

The first set of equations modeled were the vehicle's motion equations. The quarter car model was used, which isolates each individual wheel to carry the load of a quarter of the car's weight. This allows the problem to be simplified to controlling a single wheel's slip. The derived equations are Newton's Second Law for a quarter mass vehicle and Newton's Second Law for Circular Motion for the wheel. The input variables in the quarter car equations are the driving force, resistive force, motor torque, and soil torque (reaction torque generated by the soil). The acceleration taken by the two equations are integrated to calculate the velocity of the vehicle and the angular velocity of the wheel. These values along with the wheel's radius is used to calculate the slip ratio.

In order to develop a relation for the slip ratio and the forces and torques generated by the soil onto the wheel, a soil-vehicle mathematical model must be utilized. A simple model that was initially used for testing the controller was the Pacejka's Magic Tire Formula[11]. It is a trigonometric function (made up of sine and arctangent) with generally four terrain specific coefficients. The more complex model that was used for the final results was the deformable soil-rigid tire model. It is composed of three integrals to calculate the two forces and one torque. The integrated functions are the components of shear and normal stress produced by the soil. The Martian soil is represented by certain soil coefficients in the equations to calculate the shear and normal stress as functions of slip.

| | |
|---|---|
| $F_d$ | Driving Force |
| $M$ | Mass Distributed Over Each Wheel |
| $\dot{v}_x$ | Longitudinal Acceleration |
| $T_m$ | Motor Torque |
| $r$ | Wheel Radius |
| $\lambda$ | Slip Ratio |
| $N$ | Normal Force |
| $J_\omega$ | Wheel Moment of Inertia |
| $\dot{\omega}_w$ | Wheel Angular Acceleration |
| $\omega_w$ | Wheel Angular Velocity |
| $v_x$ | Vehicle Velocity |

TABLE 1: *Vehicle Model and Slip Ratio Variables.*

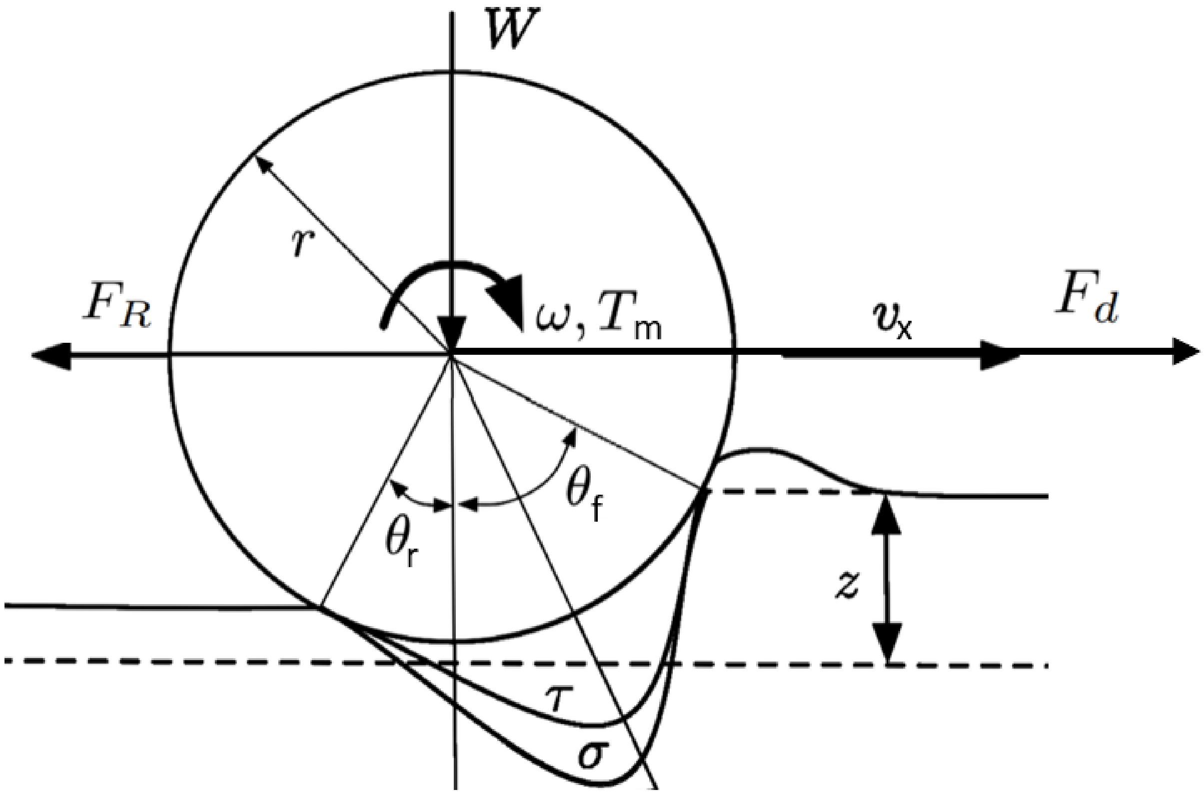



FIGURE 3: *Deformable Soil-Rigid Tire Model.*
DESCRIPTION: *The diagram represents the tire interaction with de-formable soil. The main focus of the diagram is the shear and normal stresses represented by $\tau$ and $\sigma$, respectively. The stress is experienced by the tire, and two resultant forces are generated, the driving force $F_d$ and the resistive force $F_R$.*

$$F_d = rb\int_{\theta_r}^{\theta_f} \tau(\theta)\cos\theta d\theta$$

$$F_R = rb\int_{\theta_r}^{\theta_f} \sigma(\theta)\sin\theta d\theta$$

$$T_s = r^2 b\int_{\theta_r}^{\theta_f} \tau(\theta) d\theta$$

$$\tau(\theta,\lambda) = (c + \sigma(\theta)\tan\phi)(1 - e^{h(\theta)})$$

$$h(\theta) = -\frac{r}{k}[\theta_f - \theta - (1-\lambda)(\sin\theta_f - \sin\theta)]$$

$$\sigma(\theta) = (\frac{K_c}{b} + K_\phi)(r(\cos\theta - \cos\theta_f))^n$$

EQUATION SET 2: *Terramechanics Equations.*

| | |
|---|---|
| $F_d$ | Driving Force |
| $F_r$ | Resistance force |
| $M$ | Mass Distributed Over Each Wheel |
| $\tau$ | Shear Stress |
| $\theta$ | Wheel Contact Angle |
| $c$ | Cohesion Stress of Soil |
| $\sigma$ | Normal Stress |
| $\phi$ | Friction Angle |
| $h$ | Dynamic Sinkage |
| $r$ | Wheel Radius |
| $k$ | Soil Deformation Module |
| $\theta_r$ | Soil Entry Angle |
| $\theta_f$ | Soil Exit Angle |
| $\lambda$ | Slip Ratio |
| $\dot{v}_x$ | Longitudinal Acceleration |

TABLE 2: *Terramechanics Variables.*

Parameters used in this project for the equations mentioned earlier came from two sources. These include Yoshida's article for soil properties and NASA's Curiosity specifications for the rover's dimensions and mass[13,17]. Below is a table of the parameters:

| VARIABLE | DEFINITION | VALUE |
|---|---|---|
| $r$ | WHEEL RADIUS | 0.263 m |
| $b$ | WHEEL WIDTH | 0.2 m |
| $V_0$ | INITIAL VELOCITY | 0.042 m/s |
| $M$ | ROVER MASS | 150 kg |
| $J_w$ | WHEEL MOMENT OF INERTIA | 0.82 kg $m^2$ |
| $c$ | COHESION | 1000 Pa |
| $\phi$ | FRICTION ANGLE | 0.6109 Rads |
| $n$ | SINKAGE COEFFICIENT | 1 |
| $K_c$ | COHESIVE MODULUS | 100 kN/$m^{(n+1)}$ |
| $K_\phi$ | FRICTIONAL MODULUS | 850 kN/$m^{(n+2)}$ |
| $K$ | SHEAR DEFORMATION | 0.03 m |
| $\theta_r, \theta_f$ | ENTRY/EXIT CONTACT ANGLE | 0.5917 Rads, - 0.1030 Rads |

TABLE 3: *Parameters for the Overall System.*

In order to utilize the deformable soil-rigid tire model, the integrals to calculate the forces and torque must be solved. Several methods were considered for finding the solutions. First, an analytical method was investigated. However, using Matlab's Symbolic Toolbox (a solver that can be used for integrals) only resulted in a non-simplified output. Since the equations only can be solved numerically, Taylor series approximations were used. Adding higher order derivatives to the approximations makes it more accurate, which is shown in the graph below. The 5th order approximations were utilized in Simulink to complete the mathematical model. This approximation was sufficient since higher slip ratio values (closer to one) do not occur in the simulation.

The slip ratio was determined to be the state variable, which means it is a variable that describes the state of the system. The friction or driving force, which is maximized for the ideal performance of the simulated vehicle, is a function of this slip ratio. The voltage is the control variable which is then inputted into a DC motor to generate a corresponding motor torque.

A model of a DC motor was required for the actuator of the simulation. After investigation, the Armature Circuit was a good starting point to model an ideal motor[3]. The simple Armature Circuit consists of a voltage source, resistor, inductor, and rotor with a fixed magnetic field. For the DC motor, Newton's Second Law and Kirchhoff's Voltage Law were derived. Also, proportional relations were determined for the torque and electromotive force. By utilizing these equations, an input of voltage produces a corresponding motor torque.

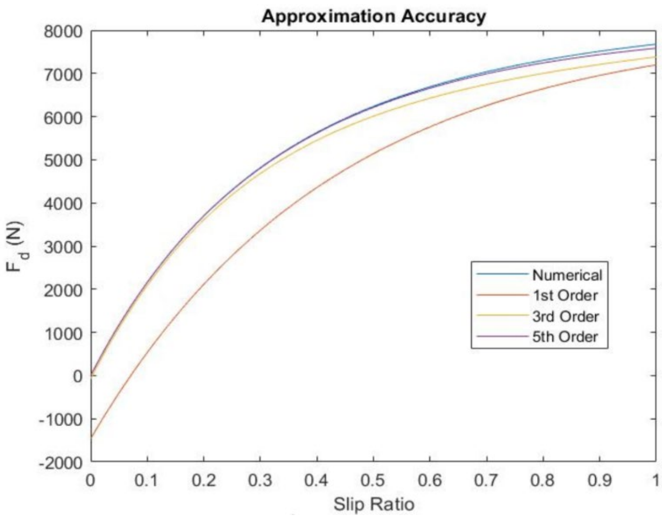



FIGURE 4: *Taylor Series Approximation for Driving Force.*
DESCRIPTION: *This graph shows the increase in the accuracy of the Taylor Series Approximation as higher order derivatives are added. The approximations are compared to the numerical curve, which is colored blue.*

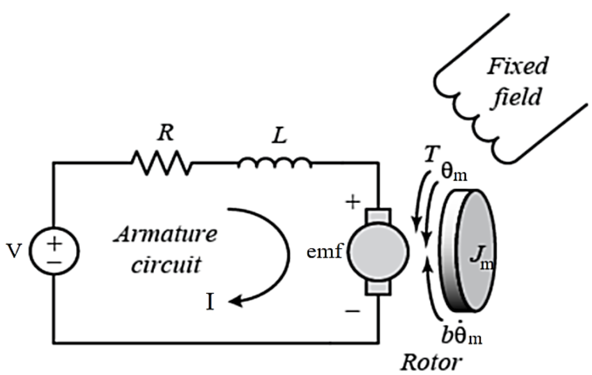



FIGURE 5: *DC Motor Armature Circuit.*
DESCRIPTION: *This diagram shows the electrical circuit on the left, and the rotor and electric field on the right. The circuit contains a voltage source, a resistor, an inductor, and a rotor.*

## List of Relevant Terms

NEGATIVE FEEDBACK LOOP – A system where the output is fed back into itself in order to influence its future output.

PLANT – The mathematical model that has an input and output (without a feedback loop)

ACTUATOR – The component of a system which is responsible for moving or controlling a device or machine.

CONTROLLER – The component of a system that uses the system's state to control its output.

QUARTER CAR MODEL – A model that simplifies a vehicle into an isolated wheel and a quarter of the total mass.

NEWTON'S SECOND LAW – The acceleration is directly proportional to the magnitude of the net force, and inversely proportional to the mass.

SLIP RATIO – The value expressed in a ratio that represents the slipping behavior of a vehicle's wheel.

DRIVING FORCE – The force, also called the friction force, is the force that causes the vehicle to accelerate forward.

PACEJKA'S MAGIC TIRE FORMULA – A simple formula that uses the slip ratio as an input and outputs the driving force. Different plugins of coefficients can model different terrains.

DEFORMABLE SOIL-RIGID TIRE MODEL – A set of equations that model a complex deformable soil like the Martian terrain.

TAYLOR SERIES APPROXIMATION – A way of approximating complex functions, using values of its derivative. Higher order expansions (more derivatives) allow for a more accurate approximation.

SHEAR STRESS – The force applied to an object in the direction parallel to the cross-sectional area.

NORMAL STRESS – The force applied to an object in the direction normal to the cross-sectional area.

ARMATURE CIRCUIT – An electrical circuit that involves a rotating part or in the case of a DC motor, an input current that interacts with a fixed magnetic field to produce a torque.

KIRCHHOFF'S VOLTAGE LAW – A form of conservation of energy for a closed electrical circuit. The law states that the sum of the voltage around a circuit must equal zero.

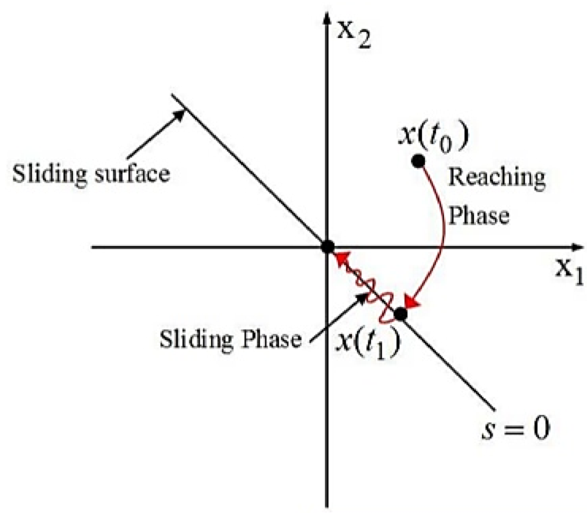
## 3 THE CONTROLLER

The purpose of the controller is to output a motor voltage signal to force the slip ratio to approach the desired value. The PID controller was first experimented with and later used to compare final results. It consists of a proportional gain, an integral gain, and a derivative gain. These multiplicative coefficients allow the user to tune the controller for different dynamical systems.

The sliding mode controller is a more advanced method than the PID. The controller, essentially, has a phase where the state variables are forced to approach a function called the sliding surface. Once on the surface, the sliding phase begins by trying to bring this sliding function to zero (as well as the error of the desired and modeled slip ratios).

FIGURE 6: *Sliding Mode Behavior.*

DESCRIPTION: *First, the sliding mode controller forces the system onto the sliding surface, denoted by the reaching phase. Then, it oscillates about this surface until the error is zero, which is called the sliding phase.*



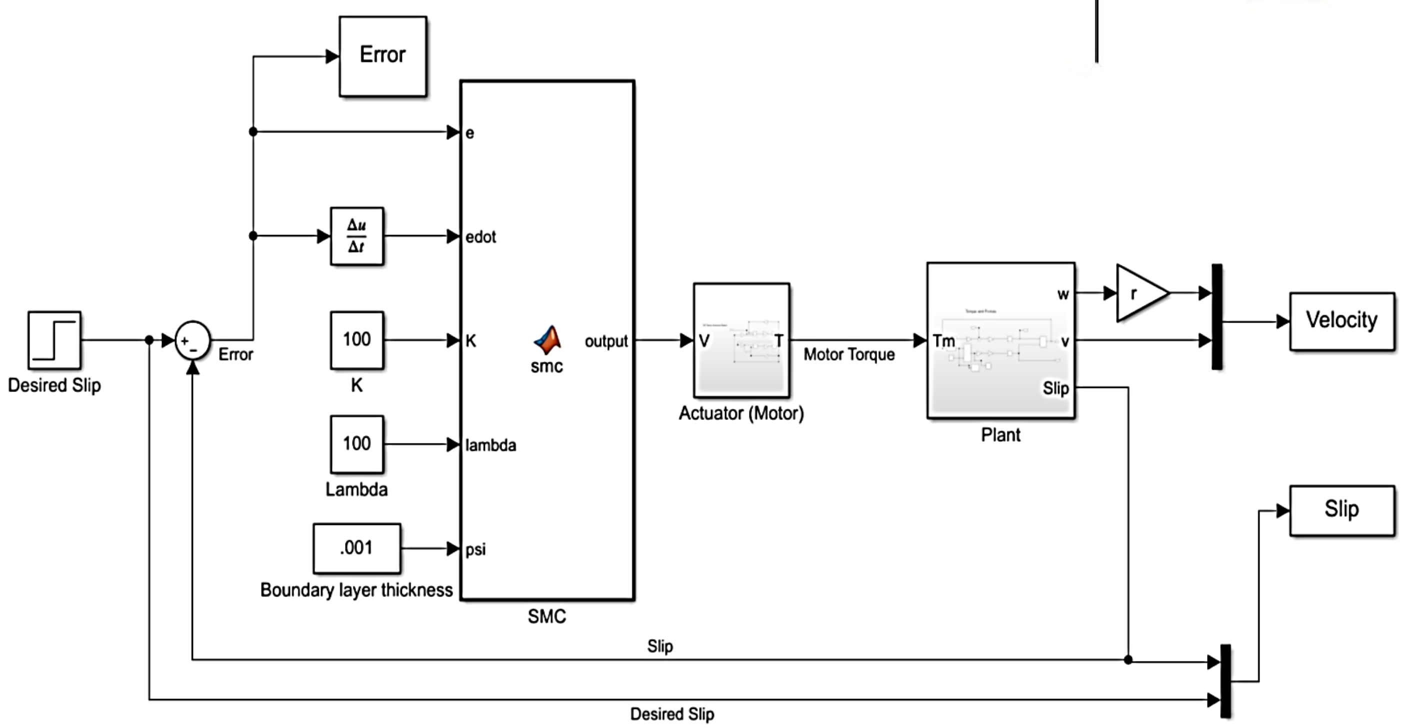




FIGURE 7: *Simulink Model.*

DESCRIPTION: *The three main components (left to right) are the controller, labeled SMC for sliding mode controller, the actuator, which is the DC motor, and the plant, which is the deformable soil-rigid tire model. The SMC is inputted with three tuning coefficients labeled K, lambda, and psi as well as the error and its rate of change. It then outputs a voltage applied to the actuator. The actuator then outputs the motor torque, which is inputted into the plant. Based on the vehicle-terrain model, the plant outputs the slip ratio which is fed back into the system to calculate the error. This completes the negative feedback loop that simulates a traction control system for a Martian rover.*

The mathematics behind the sliding mode is divided into the sliding surface design and the control input design. For the sliding surface design, the function is made up of the error and a certain number of its derivatives. For the control input design, the task is to steer the sliding surface function towards zero (in other words, to reduce the error). The control input for this project is the voltage applied to the electric motor powering the wheel. In the context of the problem, FIGURE 6 variables ($x_1$ and $x_2$) are the wheel's angular velocity and the vehicle's velocity, respectively. These variables are the state variables of the system because they are used to calculate the slip ratio. Similar to the PID controller, the sliding mode controller has coefficients for tuning. These coefficients are involved in the equations for the sliding surface function and the control input function.

After modeling the necessary mechanisms for controlling slip, the models must be integrated into Simulink for creating the simulations. To create the negative feedback system, different blocks for mathematical computation are incorporated to create a block diagram version of the equations for the model and controller. Once all the coefficients and initial conditions have been inputted, the simulation can commence.

### List of Relevant Terms

PID CONTROLLER – Proportional-integral-derivative controller. It uses a balance of the three to minimize the error of the control system.

SLIDING MODE CONTROLLER – A nonlinear control method that alters the dynamics of a system with a discontinuous control signal that forces the system to "slide" along a function that minimizes the error.

SLIDING SURFACE – The bounded function in which the sliding mode controller forces the system onto.

CONTROL INPUT – The manipulated discontinuous signal that forces the system onto the sliding surface.

TUNING – The way a control method is customized for the appropriate scenario.

STATE VARIABLES – Variables that describe the mathematical state of the dynamical system.

## 4 RESULTS

The results for the preliminary Pacejka Model simulation showed the working PID controller and different traction control responses for each of the terrains: dry asphalt, wet asphalt, concrete, snow, and ice. The desired slip ratio was different for the terrains. The value was determined by maximizing the driving force using the Pacejka's Magic Tire Formula. When looking at the plots, it is evident that the PID controller overshoots the desired slip ratio. Additionally, the oscillations in the response are not minimized. When comparing the different responses, the PID's response for ice had more oscillations at a higher frequency. This shows the lack of robustness for the PID controller. The rise and settling time for the plots were nearly identical for the five terrains. These preliminary results were useful to see the behavior of the PID for the simulated wheel and vehicle. In addition, these results already show the limitations of the PID controller for a simpler terrain model represented by the overshoot and oscillations.

The main results of this project illustrate how a sliding mode-based traction control system works on a simplified Martian terrain using a deformable soil-rigid tire model. The sliding mode controller outperformed the PID controller in stabilizing the slip ratio to a value of 0.16. Looking at the step responses, the sliding mode controller did not overshoot the desired value, while the PID did. In addition, the response of the sliding mode controller was critically damped, which was ideal. The initial response for the sliding mode controller was also faster, which is desirable for a traction control system. This is evident in the faster settling time, which was reduced by around a factor of 7 (decreased from 0.7 to 0.1 seconds). Additionally, the rise time was reduced by around a factor of 3. Looking at the tracking error plots, the error for the sliding mode controller response shows a single peak with a very small width. The same peak is evident in the PID response, but it is wider. This means the width of the initial error pulse is significantly reduced. This further supports that the sliding mode controller has better performance for minimizing the error. To finalize, the sliding mode controller is more practical for a physical rover because of its faster and more efficient response.

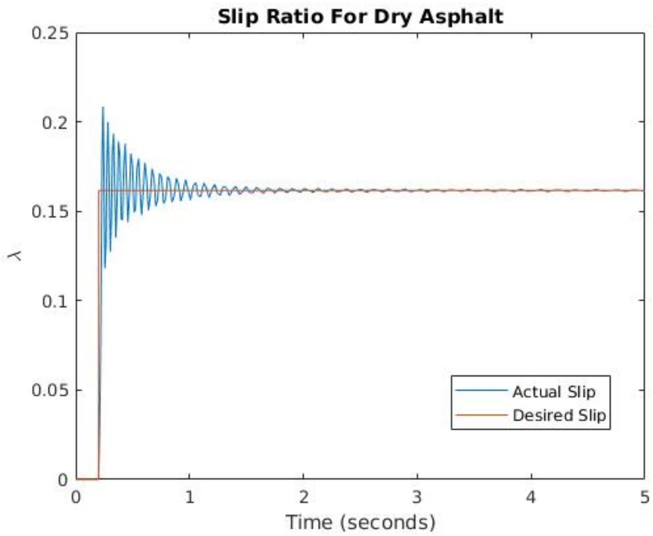



FIGURE 8: *Preliminary PID with Pacejka's Magic Tire Formula for Dry Asphalt.*
DESCRIPTION: *The plot shows the slip ratio being controlled to achieve the desired value for dry asphalt.*

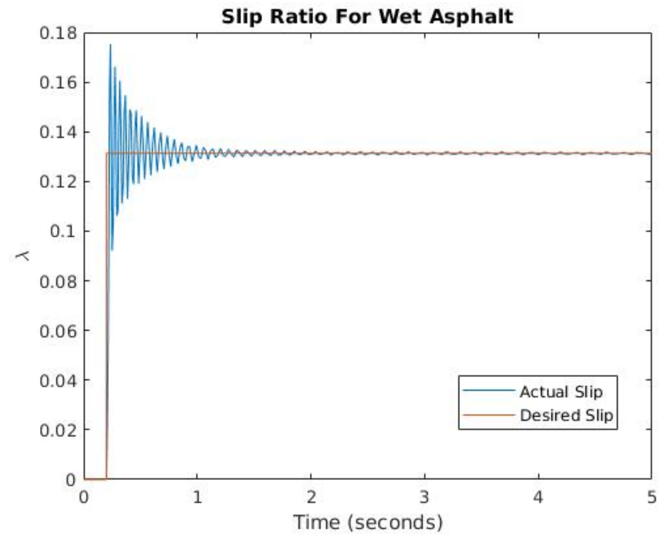



FIGURE 9: *Preliminary PID with Pacejka's Magic Tire Formula for Wet Asphalt.*
DESCRIPTION: *The plot shows the slip ratio being controlled to achieve the desired value for wet asphalt.*

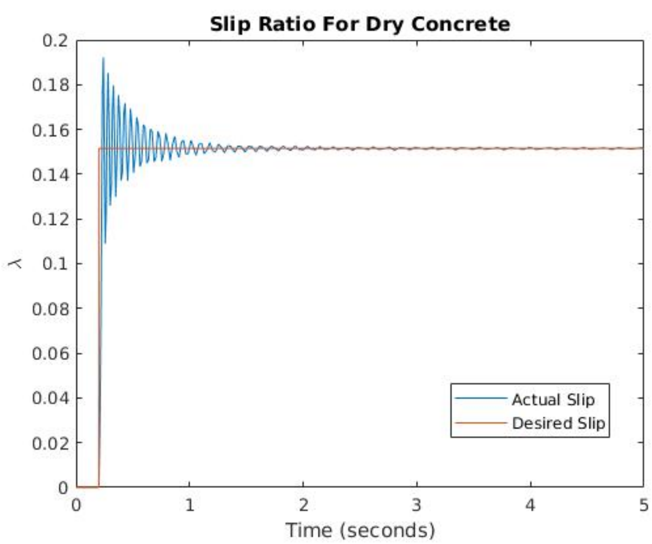



FIGURE 10: *Preliminary PID with Pacejka's Magic Tire Formula for Dry Concrete.*
DESCRIPTION: *The plot shows the slip ratio being controlled to achieve the desired value for dry concrete.*

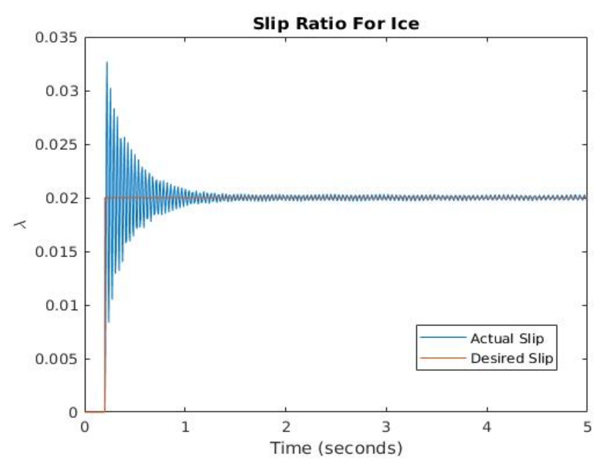



FIGURE 11: *Preliminary PID with Pacejka's Magic Tire Formula for Ice.*
DESCRIPTION: *The plot shows the slip ratio being controlled to achieve the desired value for ice.*

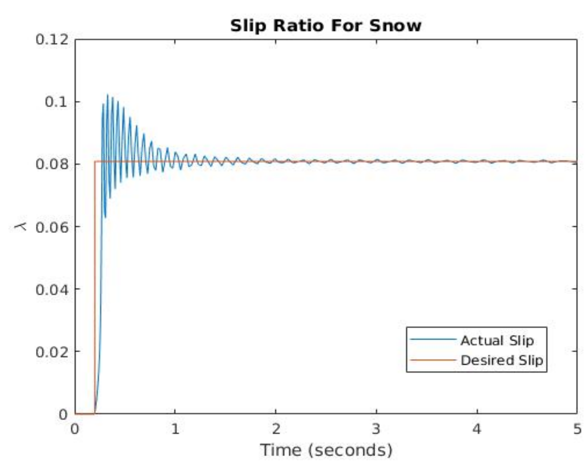



FIGURE 12: *Preliminary PID with Pacejka's Magic Tire Formula for Snow.*
DESCRIPTION: *The plot shows the slip ratio being controlled to achieve the desired value for snow.*

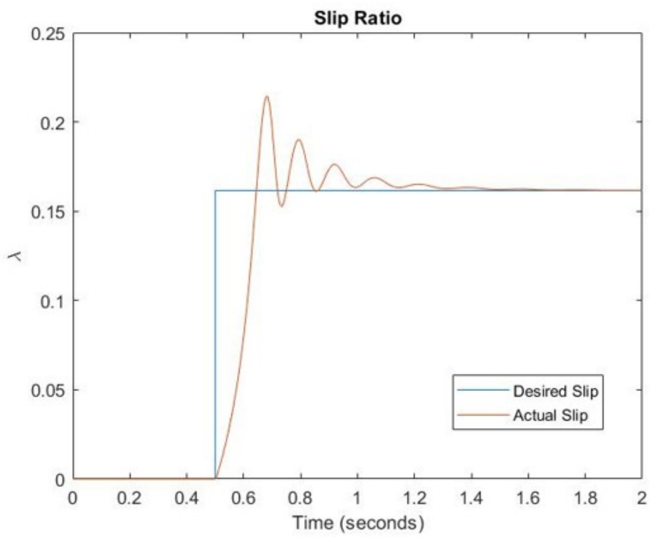



FIGURE 13: *Step Response Using PID.*
DESCRIPTION: *The slip ratio was successfully controlled using the PID controller. However, it overshot the desired slip ratio, and it created many oscillations.*

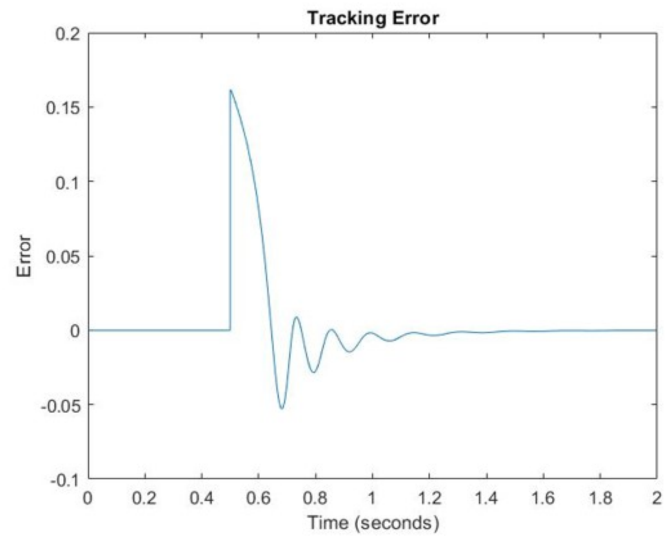



FIGURE 14: *Tracking Error Using PID.*
DESCRIPTION: *The error plot shows the delay in the PID controller's response and the oscillations present.*

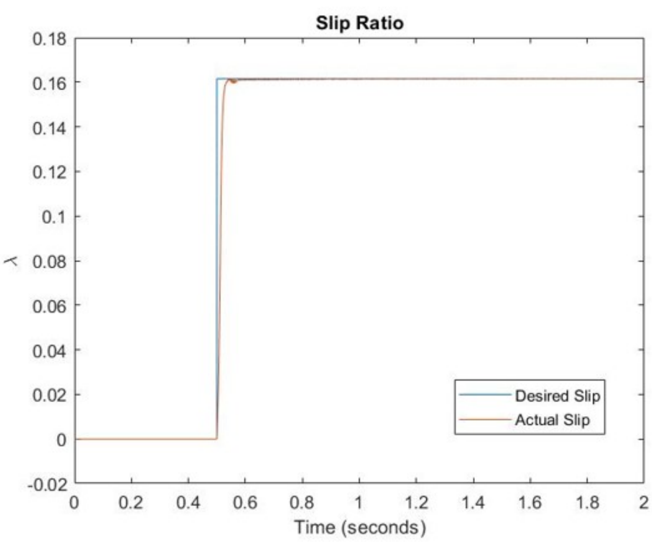



FIGURE 15: *Step Response Using Sliding Mode.*
DESCRIPTION: *The plot shows the step response of the sliding mode controller. The controller had a critically damped response with a faster rise and settling time compared to the PID.*

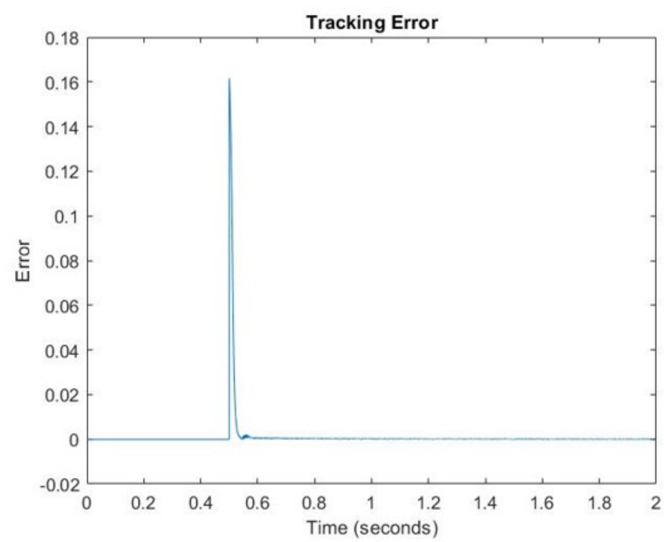



FIGURE 16: *Tracking Error Using Sliding Mode.*
DESCRIPTION: *The plot shows the tracking error of the sliding mode controller. The error decreases rapidly and does not oscillate like the PID's tracking error.*

## 5 CONCLUSION

Slip-based traction control is a very useful tool for autonomous rovers. These techniques can be applied for a wide-range of purposes: planetary exploration, rescue missions, and commercial and military endeavors. The simulations were the beginnings of creating an autonomous rover with a traction control system. The results showed the validity of the mathematical modeling and the controller design, which opened a doorway for furthering the complexity of this research. To summarize, the negative feedback-traction control system was broken down into three components: the plant, the actuator, and the controller. The plant was the mathematical model of the vehicle and terrain interaction (mostly the deformable soil-rigid tire model). The actuator was the hypothetical DC motor that powered the wheels (modeled according to a simple Armature Circuit). The (final) controller was the sliding mode, which worked more efficiently than the PID. All of these combined with the correct initial conditions simulated a slip-based traction control system for a rover on Mars.

In conclusion, the method utilized led to a better understanding of the physics of deformable soil and the limitations of a model-based traction control system. In addition, the results confirmed the hypothesis that a sliding mode controller would be more effective than a PID controller. This project further confirms the use of a sliding mode controller for a traction control system, which has been tested in recent research[6]. This project can be a trailblazer for sliding mode controller research specifically for a Martian rover. The computational results will be used on a physical rover in order to make Mars exploration easier and more efficient.

For future works, the traction control system will be tested on a physical rover (prototype being assembled in the picture above) and on a deformable test bed. In addition, theoretical work about using a sliding mode controller integrated with data-driven modeling and control will be researched in order to advance this technique. These results will be compared to that of the Taylor series approximation■

FIGURE 17: *Rover Prototype.*
DESCRIPTION: *The prototype is a six-wheeled, rocker-bogie suspension rover. The frame and wheels were 3D printed. The computer onboard the rover is an Arduino Uno. The green cylinders are LiPo batteries to power the rover. The motor and electronic speed controllers have not been added yet.*

## 6 ACKNOWLEDGEMENTS

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